Fermilab Proton Accelerator Complex Evolution (ACE) plan

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21 March 2023

P5 Fermilab Town Hall

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Fermilab Accelerator Complex – a National User Facility

- Fermilab's accelerator facility delivers particle beams that enable the high energy physics mission. The laboratory also leads in innovating and realizing future accelerators for scientific discoveries.
- This talk presents a strategy for upgrading the Fermilab accelerator complex with the following key criteria
  - **Primary focus on providing maximum 2.4 MW of 120 GeV protons to LBNF**
  - Reduce the time for LBNF/DUNE to achieve first results
  - Fully realize the investment made for PIP-II and LBNF by enabling **sustainable high-reliability operation**
  - Enable other science opportunities by expanding the complex **capacity and capabilities**

Fermilab Accelerator Complex strategy

- In summer 2022 Fermilab Director assembled a group to develop strategy for upgrading the Fermilab accelerator complex

Proton Intensity Upgrade
Central Design Group

Robert Ainsworth, Giorgio Apollinari, Tug T. Arkan, Sergey Belomestnykh, Pushpalatha C. Bhat, S.J. Brice, Brian Chase, Mary E. Convery, Steven J. Dixon, Jeff Eldred, Grigory Eremeev, Brenna Flaugher, Jonathan D. Jarvis, Sergo Jiindariani, David Johnson, Jonathan Lewis, Richard Marcum, Sergei Nagaitsev, David Neuffer, Donato Passarelli, Frederique Pellemoine, William A. Pellico, Sam Posen, Eduard Pozdeyev, Alexander Romanenko, Arun Saini, Kiyomi Seiya, Vladimir Shiltsev, Nikolay Solyak, James M. Steimel, Diktys Stratakis, Alexander A. Valishev, Mayling L. Wong-Squires, Slava Yakovlev, Katsuya Yonehara, Robert Zwaska

- Working in close collaboration with the Science Priorities group, the committee developed the Accelerator Complex Evolution (ACE) plan

Accelerator Complex Evolution (ACE) plan

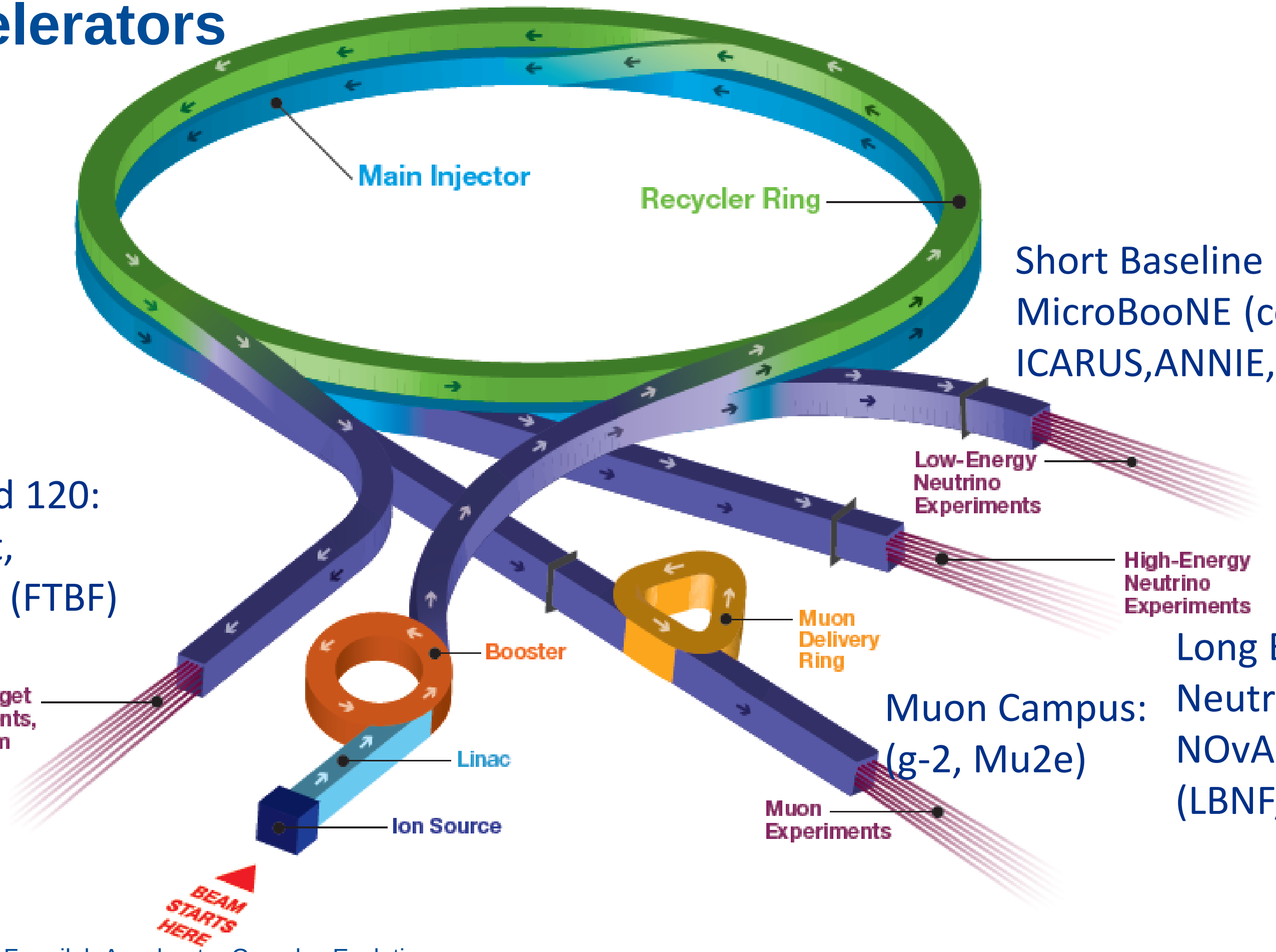
Our vision is centered on the ACE plan that has two components

- The Main Injector cycle time shortening, target systems upgrade and reliability improvement work to be carried out through the 2020's to enable delivery of more protons on target will accelerate the achievement of the DUNE science goals with respect to the present PIP-II plan
- Simultaneously a Project would be established to build Booster replacement. The implementation of Booster replacement would
  - **Reliably deliver even more beam power to LBNF** to ensure CP Violation measurement in DUNE Phase II
  - **Considerably enhance beam capabilities for a broader physics program**
  - **Provide a robust and reliable platform for the future evolution of the Fermilab accelerator complex**, possibly including a proton source for multi-TeV accelerator research

Booster replacement

- A new machine to replace the Booster would have **superior capacity, capability, and reliability**
- **Booster has fundamental limiting features built into the machine core**
  - Combined-function magnets with transition-crossing lattice, resulting in particle losses
  - No vacuum chamber with exposed magnet laminations, high beam impedance, losses
- Booster served the laboratory for over 50 years, and could be a **risk for long-term reliability**
- Development of a modern machine would present a tall challenge for America's accelerator laboratory and **capitalize on emerging technologies** created by ongoing accelerator R&D (SRF, IOTA, etc.)
  - Maintain excellence in accelerators, invest in future workforce
  - Strengthen collaborations with partners

Fermilab accelerators



Short Baseline Neutrino: MicroBooNE (completed), ICARUS,ANNIE, SBND

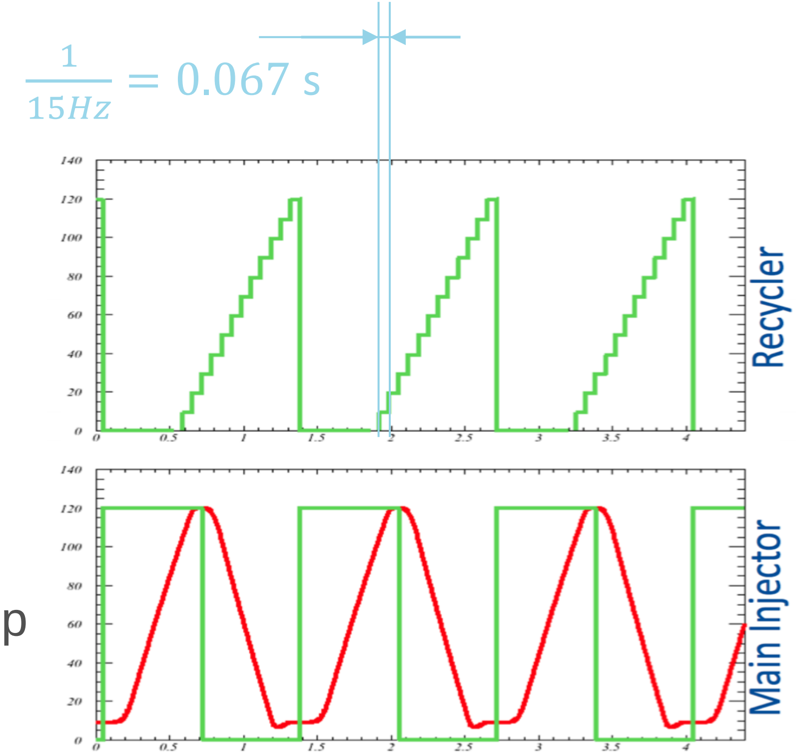
SwitchYard 120: SpinQuest, test beam (FTBF) NOvA

Muon Campus: (g-2, Mu2e)

Long Baseline Neutrino: NOvA, (LBNF/DUNE)

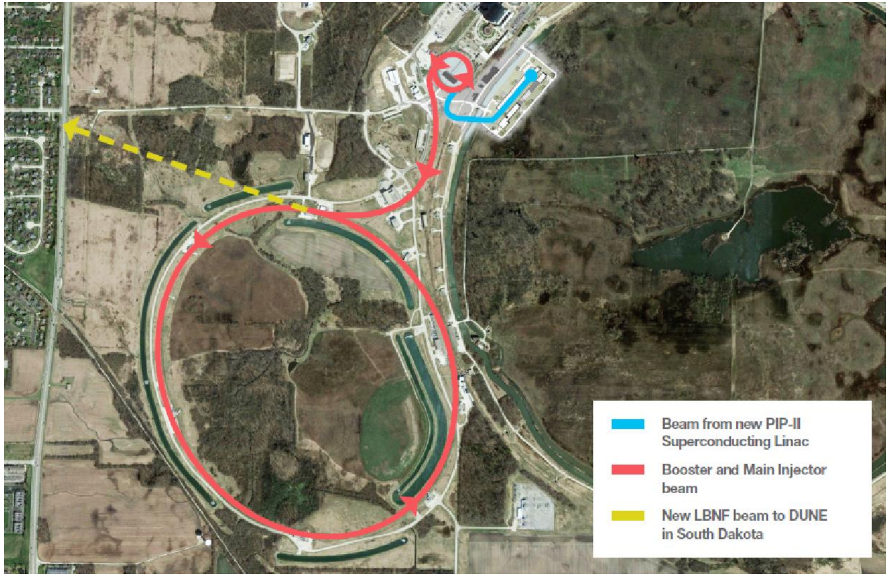
Introduction to Fermilab accelerators

- **H^- linac (1970, 1993, 2012)**
  - 400 MeV linac ~20mA
- **Booster synchrotron (1970)**
  - H^- stripping injection (1978)
    - 16 turns to ~4.7×10^{12}p per pulse
  - Ramp from 0.4 to 8 GeV at 15 Hz
- **Recycler (1998)**
  - 3.3 km permanent magnet 8 GeV ring
  - Slip-stacking 12 Booster batches, ~56×10^{12}p
- **Main Injector (1998)**
  - 8 to 120 GeV ramp, cycle time 1.2 s



Accelerator Complex in PIP-II / LBNF era

- New PIP-II SRF linac provides beam for injection into Booster at energy increased to 800 MeV from present 400 MeV
- Booster cycle rate is upgraded to 20 Hz from 15 Hz
- Proton flux at 8 GeV increases 2 times resulting in beam power from Main Injector to reach 1.2 MW



- Wide-reaching modernization campaign and series of upgrades will further extend the scientific reach, improve reliability
- Position the accelerator complex for next-generation upgrades

2014 P5 R14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for PIP-II should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Path to higher number of neutrinos

The ACE plan aims to develop the Fermilab accelerator complex capabilities beyond PIP-II

The total integrated number of produced neutrinos will be determined by

1. Maximum proton flux produced by the accelerator
2. Overall efficiency of operations
3. Ability of target station to convert protons to neutrinos

ACE – Path to higher number of neutrinos: 1) proton flux

First component of the ACE plan is to increase proton beam power beyond PIP-II performance specifications.

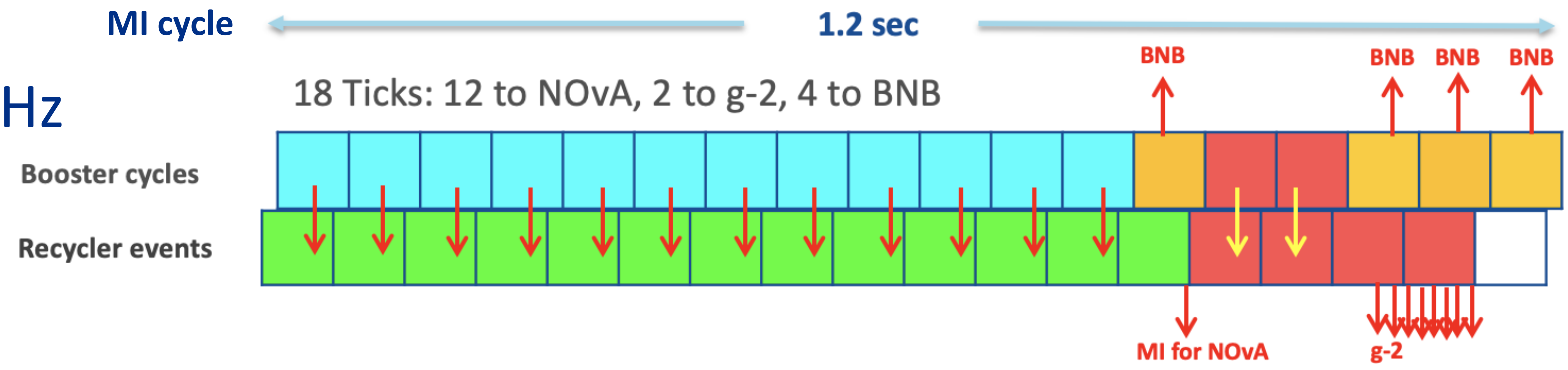
The proton flux to LBNF is a function of

$$P = \frac{eNE}{T}$$

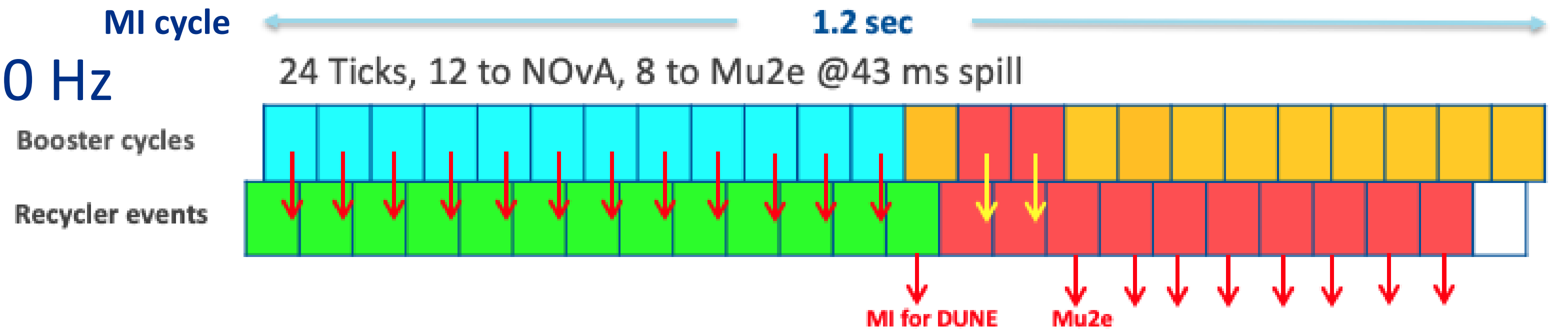
1. Main Injector cycle time
   - PIP-II increases particle flux from Booster by factor ~2 from present level to achieve 1.2MW with 1.2s MI cycle. Shortening MI cycle would allow *taking full advantage of the PIP-II beam* for increasing LBNF proton flux *without raising MI intensity*
2. Main Injector beam pulse intensity
   - Requires more 8GeV beam beyond PIP-II i.e. *Booster replacement*
   - Requires *MI upgrades for higher intensity*.

Proton economics for multiple users with a flexible timeline

Present 15Hz

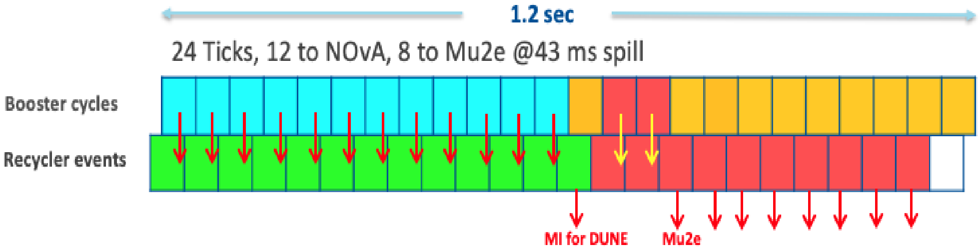


PIP-II era 20 Hz



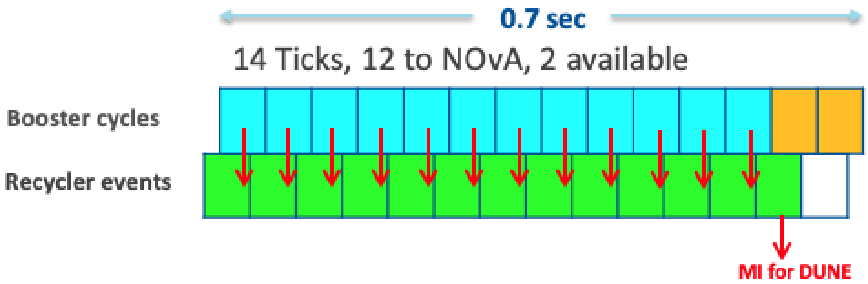
Main Injector beam power in numbers

		PIP-II Booster	
Operation scenario	**Present**	**PIP-II**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	s
Booster intensity	**4.5**	**6.5**	10^{12} p
Booster ramp rate	15	**20**	Hz
Number of Booster batches	12	12	
MI power	0.865	**1.2**	MW
cycles for 8 GeV	6	12	
Available 8 GeV power	29	**83**	kW



Main Injector beam power in numbers – ACE

		PIP-II Booster			Booster Replacement			
Operation scenario	**Present**	**PIP-II**	**A**	**B**	**C**	**D**	**E**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.5**			**6.5**		**10**		10^{12} p
Booster ramp rate	15			**20**		20		Hz
Number of batches	12		12		12	12	9	
MI power	0.865	**1.2**	1.7	**2.14**	1.9	**2.5**	2.4	MW
cycles for 8 GeV	6	12	6	2	12	6	5	
Available 8 GeV power	29	**83**	56	**24**	128	**85**	92	kW



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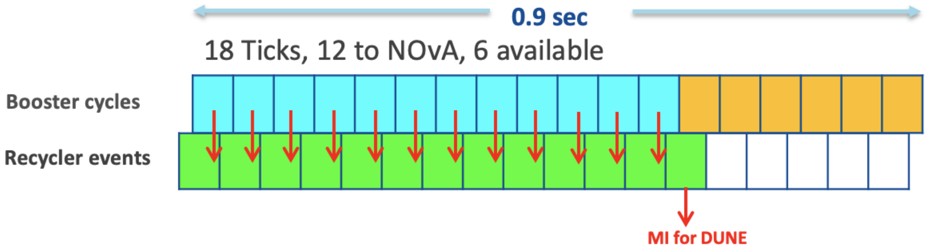
Main Injector beam power in numbers – ACE

		PIP-II Booster			Booster Replacement			
Operation scenario	**Present**	**PIP-II**	**A**	**B**	**C**	**D**	**E**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.5**	**6.5**			**10**			10^{12} p
Booster ramp rate	15	**20**			20			Hz
Number of batches	12	12			12	12	9	
MI power	0.865	**1.25**	1.666	**2.14**	1.922	**2.563**	2.472	MW
cycles for 8 GeV	6	12	6	2	12	6	5	
Available 8 GeV power	29	**83**	56	**24**	128	**85**	92	kW



ACE – Path to more of neutrinos: (2) operations efficiency

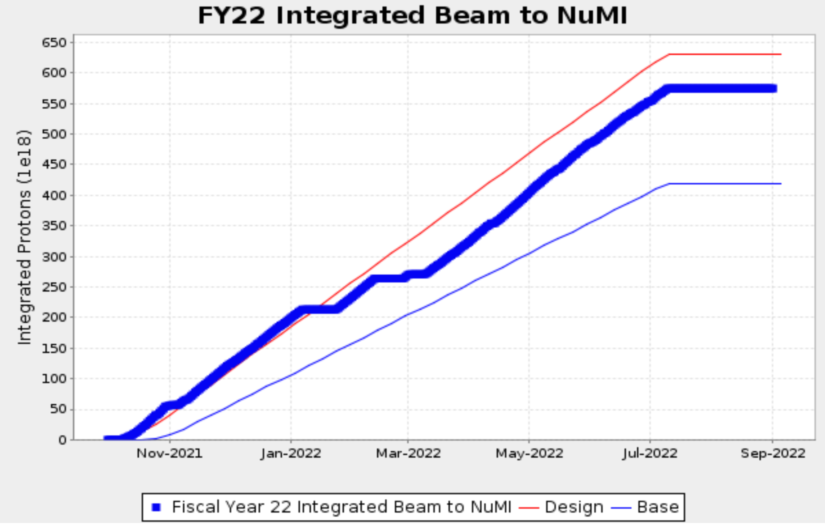
Key factors for beam delivery to experiments

1. High-power operation (maximum proton flux).
   - Good tuning, low losses.
   - FY22 <P>=76% of P_{max} Record power of 0.895 MW reached!
2. High uptime during running periods.
   - Achieved by through reliability and the ability to rapidly repair of equipment that breaks.
   - FY22 uptime 69% of scheduled
3. Maximize the length of the running periods each year.
   - Minimum duration of shutdowns.
   - FY22 scheduled 77% of CY

Overall FY22 efficiency 41%, DUNE/PIP-II goal 57%

To maximize physics, most productive approach

- **Invest in reliability, availability and stability**
- **Reduce shutdown duration, improve work planning**



Long-term reliability at risk with present Booster

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Considerations for shortening the MI cycle time

1. Magnets
    - Main risk: Magnet lifetime - the magnet failure modes are not fully clear. Doubling the repetition rate may lead to an increase in magnet failures.
    - Mitigation - revive production line to replace magnets as needed. MI quadrupoles are presently failing 1-2 per year.
2. Electrical power
3. Power distribution and control
4. RF accelerating system. Must be upgraded to reach >2MW in any scenario.
5. Beam dynamics, losses and shielding
6. Target station. Must be upgraded to reach >1.2MW in any scenario.

Workshop/Meeting in January investigated/reviewed technical implications for the complex - https://indico.fnal.gov/event/57326/

Main Injector is becoming the center piece of any scenario

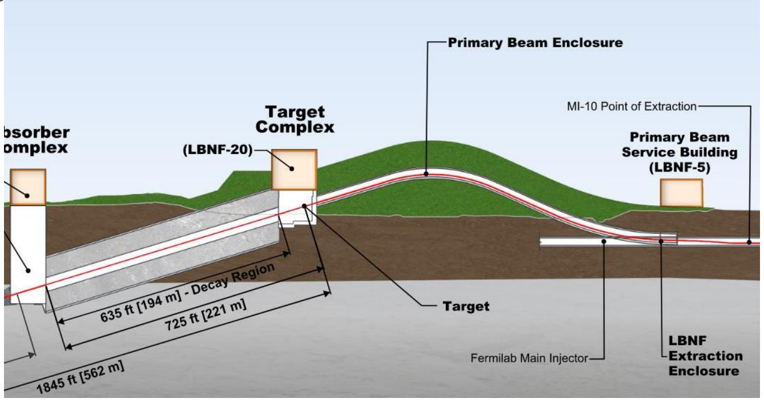
The Main Injector **reliability** and **cycle time reduction** are tightly coupled

- Modernize infrastructure to run reliably in the DUNE era
  - Site power (KRS, feeders)
  - MI power (transformers, supplies and related systems)
  - Cooling
  - Quadrupole magnets
  - LLRF
  - Controls, ...

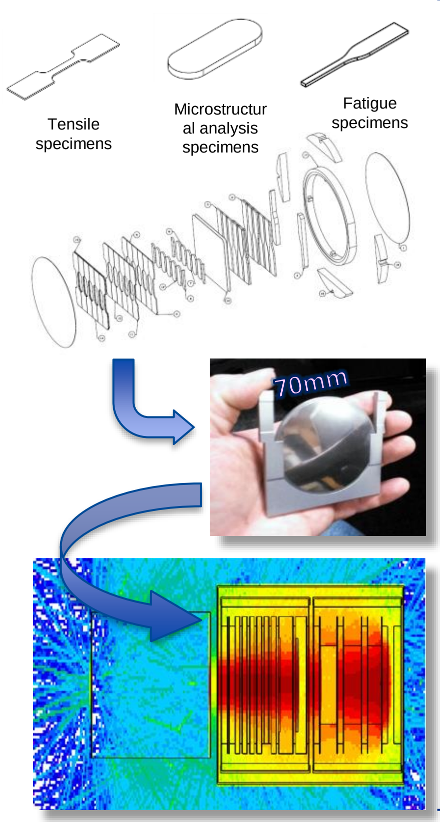
- These upgrades constitute most complexity and cost for the entire 1st phase of ACE plan.

Main Injector for >1.2MW

- Loss control and shielding are specific to running at high power >1.5MW
  - May require addition of shielding
- RF system upgrade is necessary – adding 17 RF stations. (coupled to modernization: running Main Ring RF cavities into 2030-s!)
  - Involves civil construction for additional RF gallery, penetrations, anode supplies, and transformers
- Feedback system
- LBNF primary beamline was designed for 2.4MW, upgrade to enable pulsing at 0.65 s is relatively straightforward



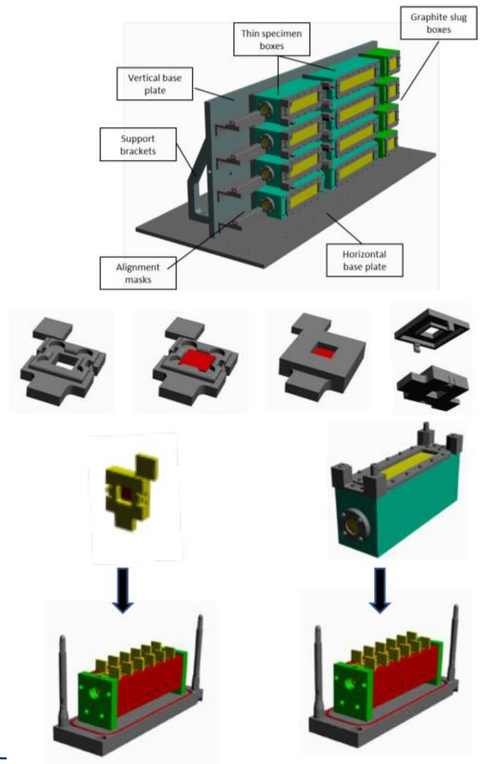
Target materials R&D on critical path to 2+ MW target



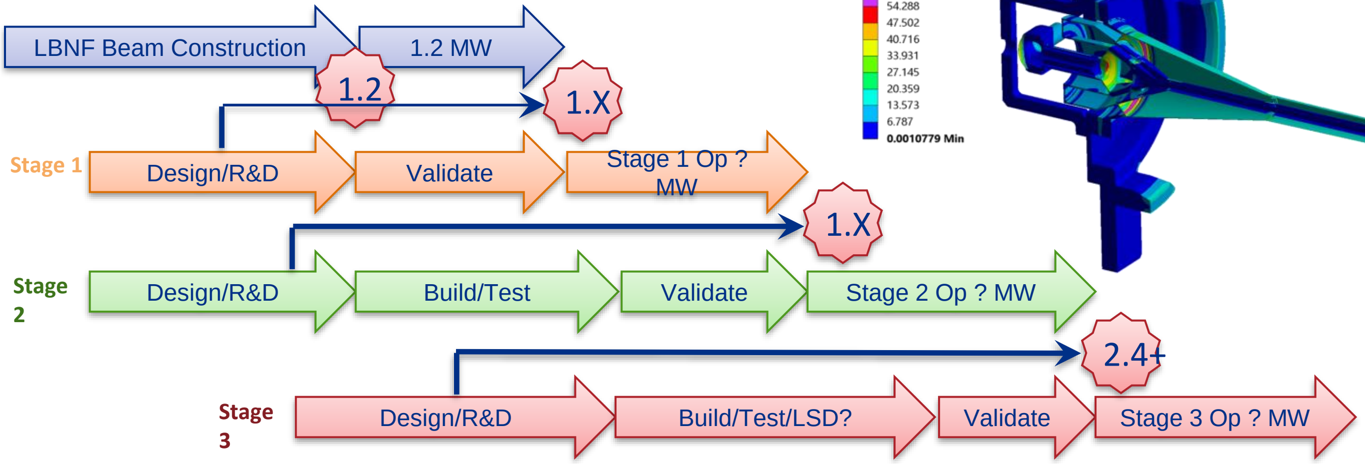
- Identify **candidate materials**, grades, preparations, and conditions in operation
  - Develop the operation conditions for testing (radiation damage, static stresses, shock, temperature, fatigue cycles
- **High-energy proton irradiation** of material specimens
  - Reach representative levels of radiation damage in characteristic conditions
- **Pulsed-beam Experiments** of irradiated specimens
  - Duplicate loading conditions of beam interactions
- **Non-beam PIE** (Post-Irradiation Examination) of irradiated specimens
  - Measure change of material properties (strength, CTE, density, hardness, ductility, thermal conductivity, …)
  - Material Science investigations of microscopic structural changes
  - High-cycle fatigue testing

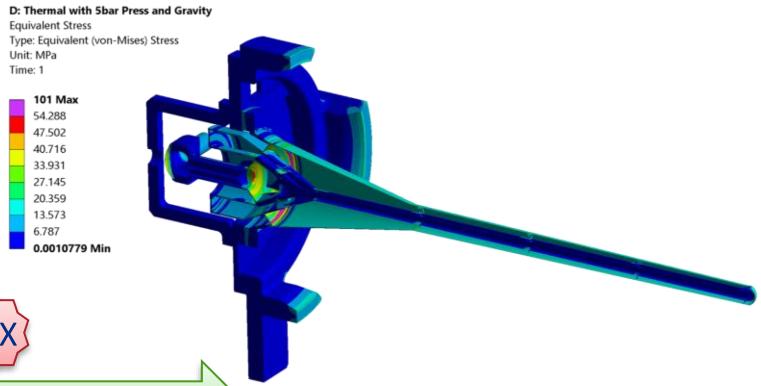
Five-years cycle of design, irradiate, pulsed-beam, PIE (minimum from previous experience)

Needs to start ASAP to inform 2.4 MW Target Design



Staged beam-power ramp-up strategy





- **Stage 1** – Push current designs (1.2 MW) to validated limitations
- **Stage 2** – Design and build 2nd generation components with modifications to existing designs to raise limits while maintaining reasonable useful Nu flux/POT
- **Stage 3** – Design and build fully optimized next generation systems to take full advantage of maximum POT from accelerator complex (may not be needed)

Materials R&D results needed to inform design modifications for higher beam power

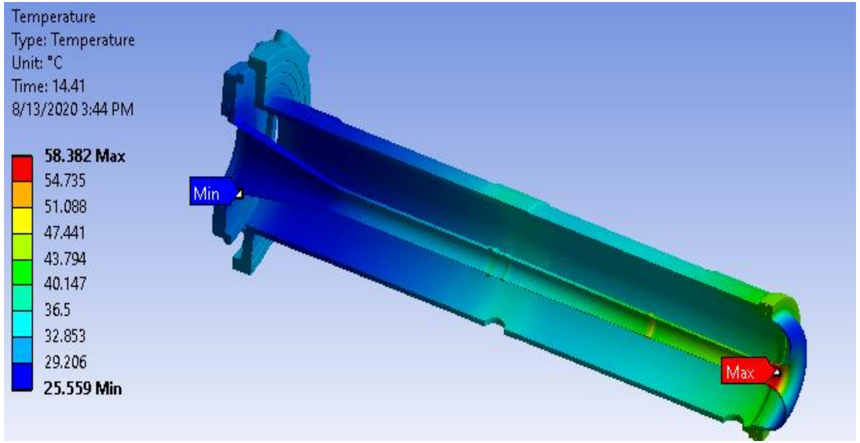
Horns for 2.4 MW performance

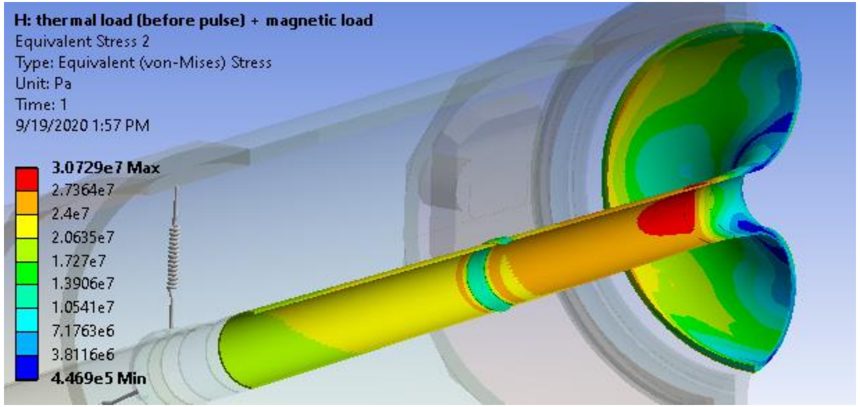
Horn A requires reanalysis, and likely redesign

- 1.2 MW analysis indicates 2.7 safety factor on fatigue endurance limit
  - Non-trivial scaling for fatigue endurance with changing mean temperature and cycle amplitude
- Likely redesign to:
  - Avoid beam heating in critical locations
  - Strengthen structure in critical locations

Horns B&C see less beam heating

- Safety factor: 7.3 for 1.2 MW operation
- Require reanalysis, but less likely redesign





Booster replacement scenarios

Considered 6 Configurations: 3 SRF Linac, 3 Rapid-Cycling Synchrotron (RCS)

In addition to 2.4MW to LBNF, the options enable new science 'spigots':

- 2 GeV Continuous wave (CW)
- 2 GeV Pulsed Beam (~ 1MW)
- 8 GeV Pulsed (~ 1MW)

RCS Configurations:

C1a) 10 Hz: metallic vac. chamber

C1b) 20 Hz: ceramic vac. chamber

C1c) 20 Hz: ceramic vac. chamber, high current linac

SRF Linac Configurations:

C2a) Basic: small increase in PIP-II current, demonstrated XFEL RF

C2b) High duty factor RF source: small increase in PIP-II current

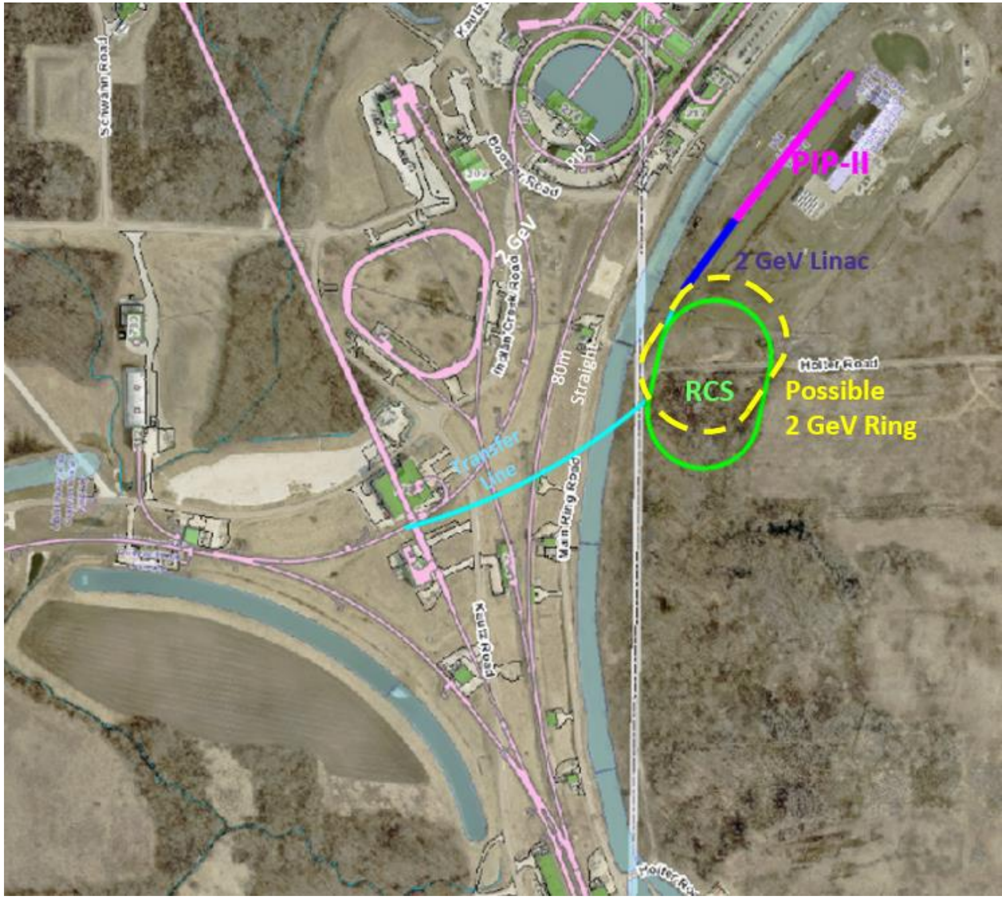
C2c) Higher Current PIP-II: significant current upgrade (5mA)

The specific upgrade scenario to be selected and developed with community input and informed by P5 and DOE decisions

Example 1

Configuration C1b:

- 20Hz RCS + 2 GeV AR
- Main elements
  - 1-2GeV Linac
  - 20Hz 8GeV RCS
  - 2 GeV Accumulator Ring
  - MI Upgrades
  - Transfer Lines



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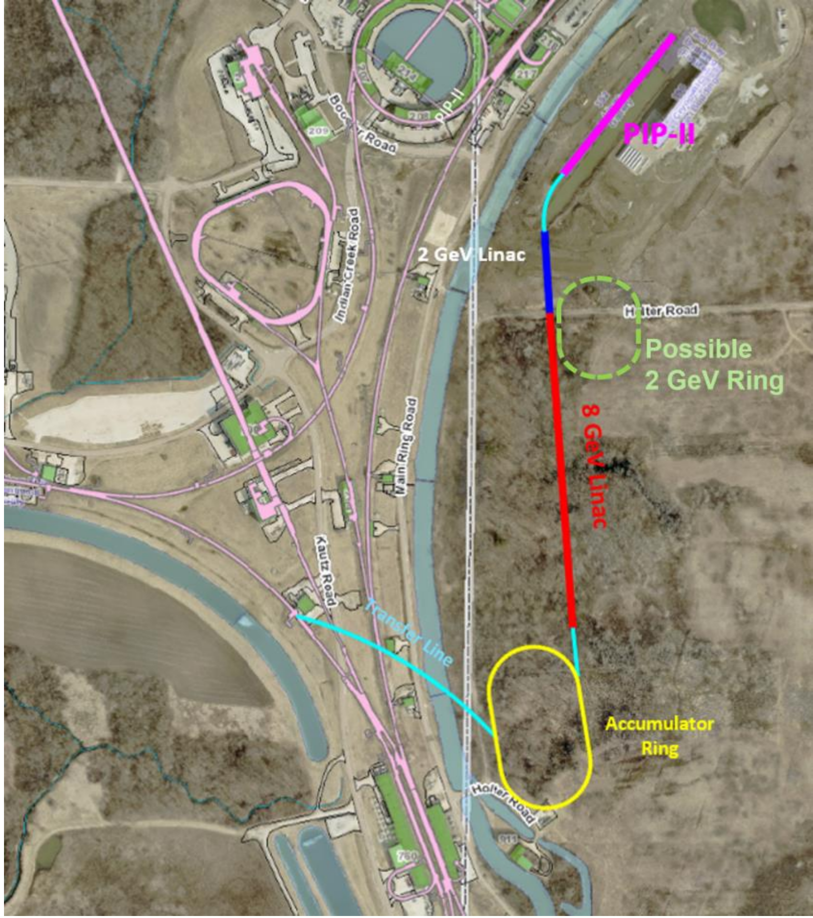
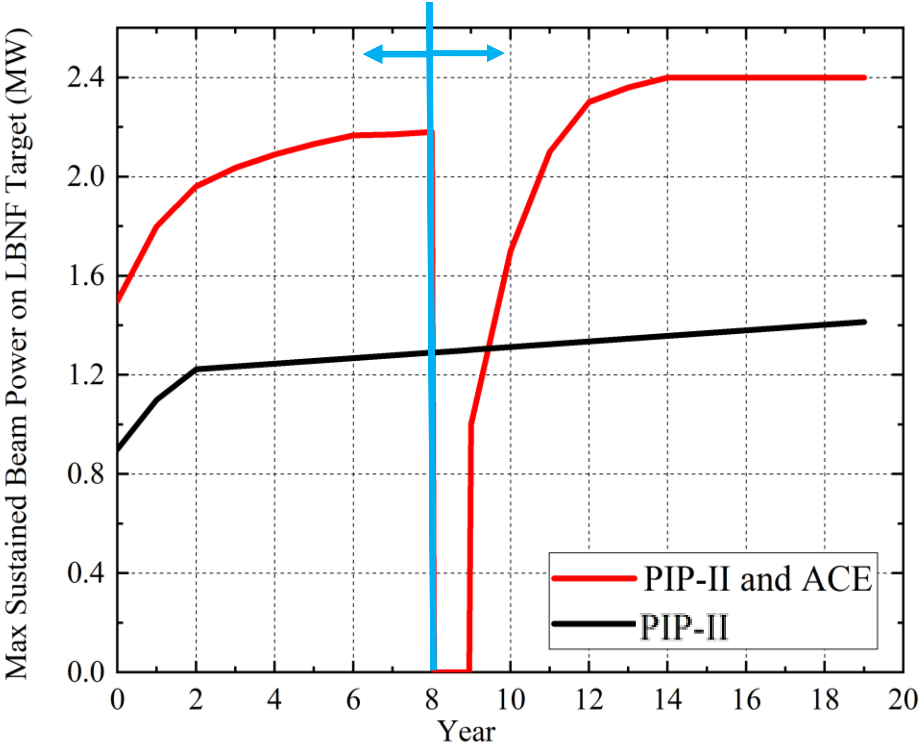
Example 2

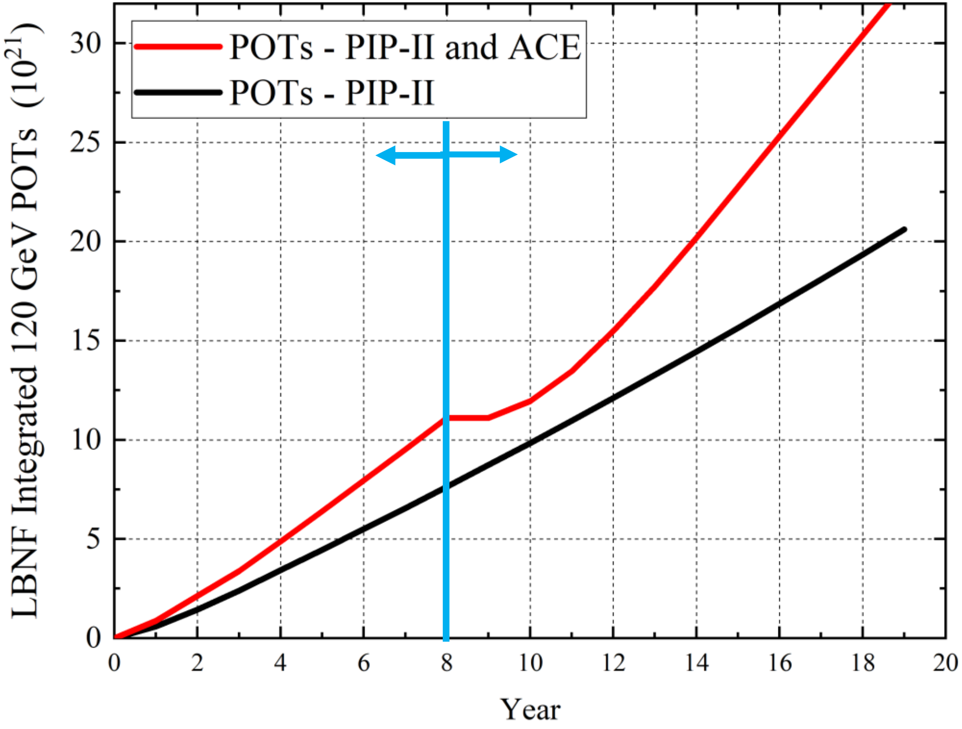
Configuration C2a:

- SRF Linac + 8 GeV AR option
- Main elements
  - 1-2GeV Linac
  - 8GeV Accumulator Ring
  - 8GeV SRF Linac
  - MI Upgrades
  - Transfer Lines

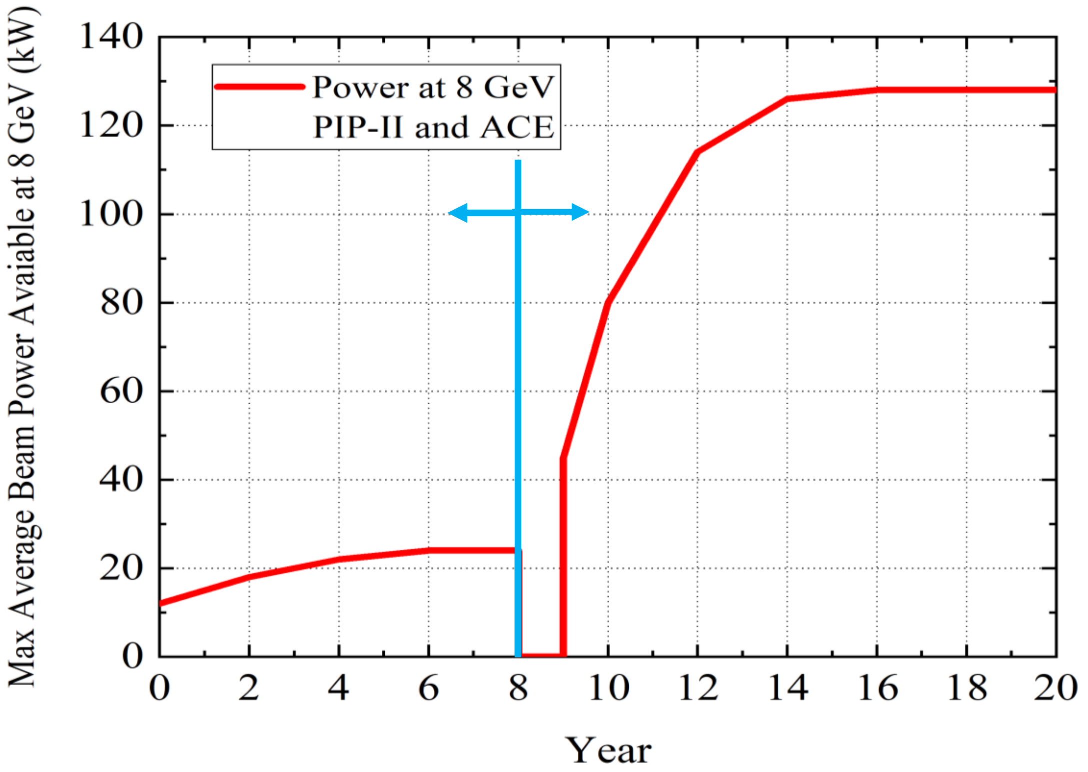


DUNE power and POT implications





8 GeV capacity implications



Request to P5

The Accelerator Complex Enhancement (ACE) plan capitalizes on the PIP-II investment and delivers both higher POT to LBNF than PIP-II alone could provide and a Booster Replacement that will provide even higher rates of POT accumulation in addition to a modern and flexible Fermilab Accelerator Complex. We ask P5 to support the ACE plan that includes the following key components

1. Upgrades to Main Injector accelerator systems and infrastructure to enable beam power above 1.2MW through faster cycle time and efficient operations of the complex with the aim of achieving DUNE goals as fast as possible, performed as series of AIP and GPP between 2024 and 2032.

2. Accelerated profile of high-power target system R&D to enable above 1.2MW operations in DUNE Phase I.

3. Establishment of a Project for Booster replacement with superior capacity, capability, and reliability to be tied to the accelerator complex at a time determined by the DUNE physics.

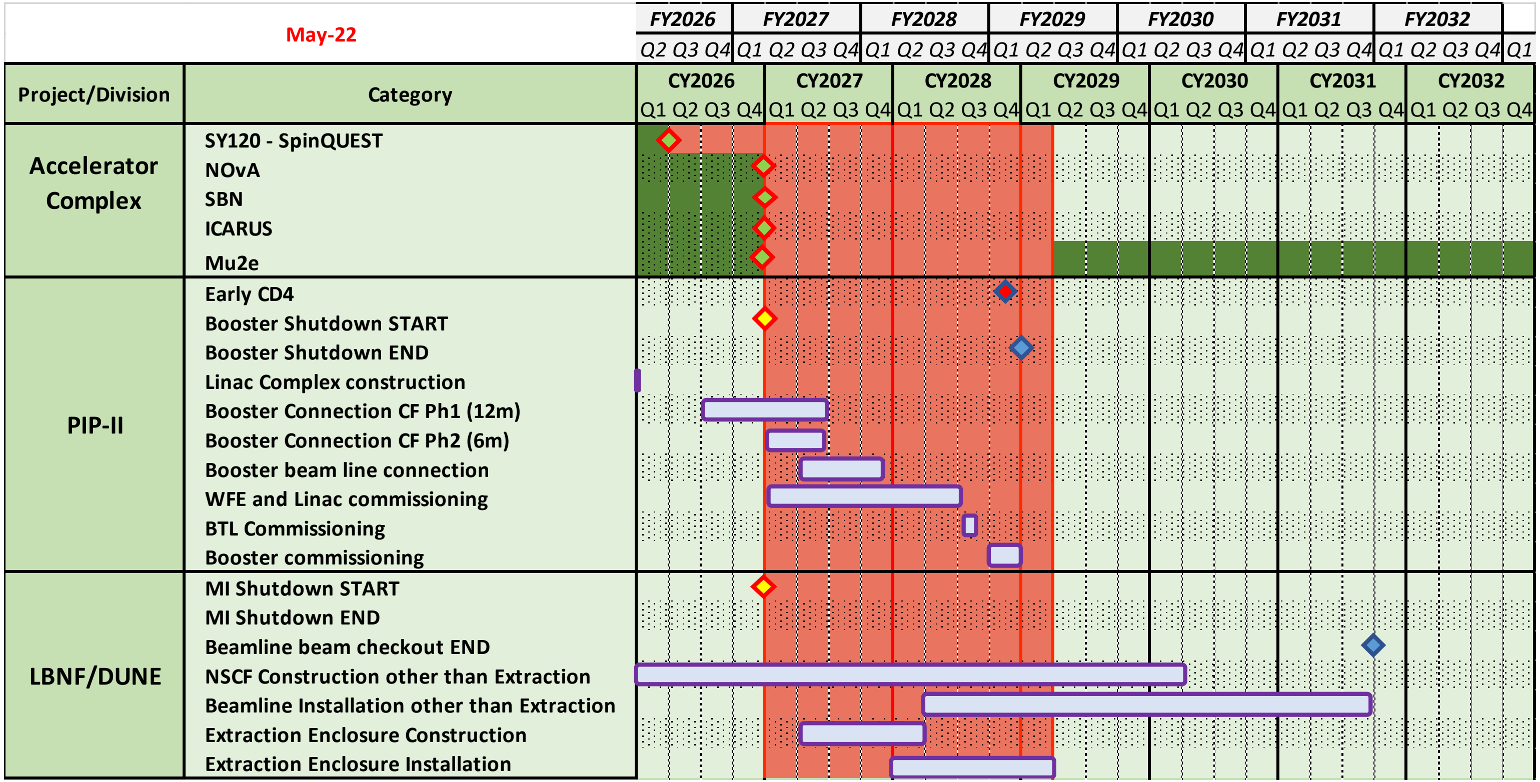
Extra slides

Beam delivery plan

		FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF	Sanford		DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	ν
PIP-II	Fermilab		LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LB NF	LBNF	
NuMI	MI		open	2x2	2x 2	2x2	2x2	2x2					
	MI	NO	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA					
BNB	B	µB	open	open	open	open	open	open			open	open	
	B	IC	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS			open	open	
	B	SB	SBND	SBND	SBND	SBND	SBND	SBND			open	open	
Muon Complex		g-2	g-2	g-2	g-2	g-2							μ
		Mu	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	
SY 120	MT	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	p
	MC	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	
	NM4	Sp	SpinQ	SpinQ	S pinQ	SpinQ	SpinQ				open	open	
LINAC	MTA		ITA	ITA	ITA	ITA	ITA	ITA					

Construction/Commissioning	
Run	
Subject to further review	
Summer Shutdown	
Long Shutdown	

PIP-II and LBNF accelerator milestones



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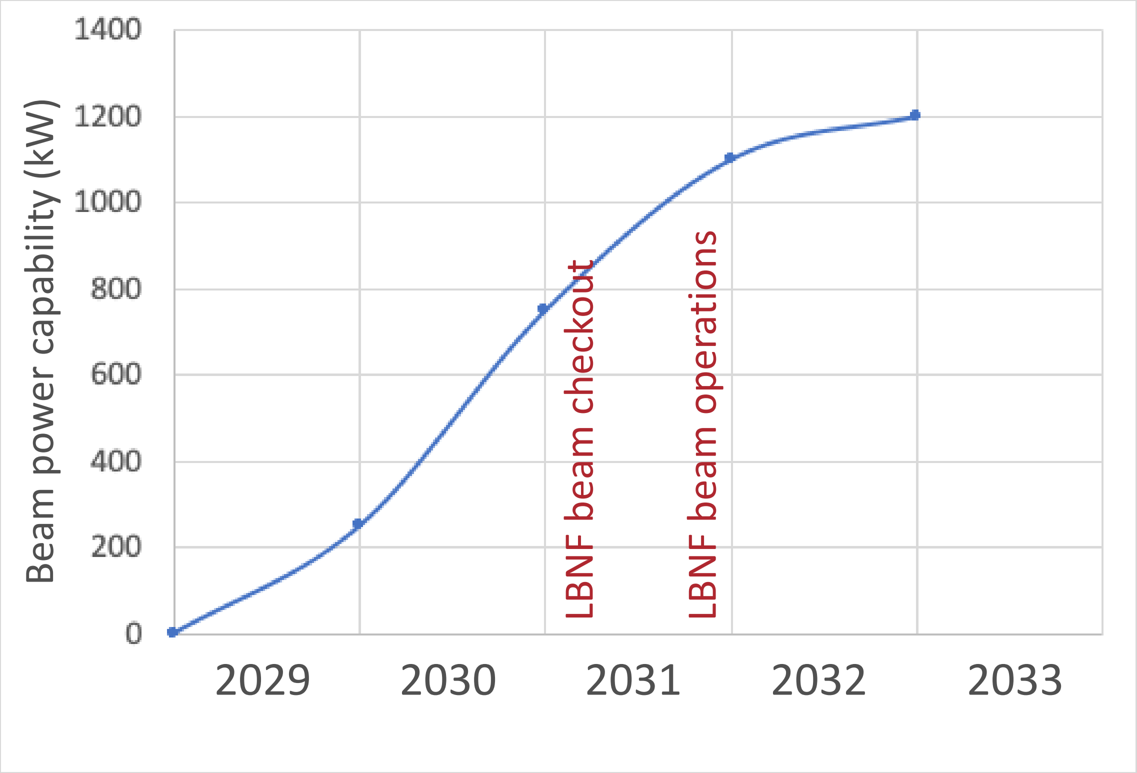
PIP-II LBNF/DUNE power ramp up



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